

DISCOVERY AND EARLY MULTI-WAVELENGTH MEASUREMENTS OF THE ENERGETIC TYPE IC SUPERNOVA PTF12GZK: A MASSIVE-STAR EXPLOSION IN A DWARF HOST GALAXY

SAGI BEN-AMI^{1,2}, AVISHAY GAL-YAM¹, ALEXEI V. FILIPPENKO³, PAOLO A. MAZZALI^{4,5,6}, MARYAM MODJAZ⁷, OFER YARON¹, IAIR ARCAVI¹, S. BRADLEY CENKO³, ASSAF HORESH⁸, D. ANDREW HOWELL^{9,10}, MELISSA L. GRAHAM^{9,10}, J. CHUCK HORST¹¹, MYUNSHIN IM¹², YISEUL JEON¹², SHRINIVAS R. KULKARNI⁸, DOUGLAS C. LEONARD¹¹, ELENA PIAN^{13,14,6}, DAVID J. SAND^{9,10,15}, MARK SULLIVAN¹⁶, JULIETTE C. BECKER⁸, DAVID BERSIER¹⁷, JOSHUA S. BLOOM^{3,18}, MICHAEL BOTTOM⁸, PETER J. BROWN¹⁹, KELSEY I. CLUBB³, BEN DILDAY^{13,14}, RICHARD C. DIXON²⁰, ARYEH L. FORTINSKY¹, DEREK B. FOX²¹, LUIS A. GONZALEZ²², AVET HARUTYUNYAN²³, MANSI M. KASLIWAL²⁴, WEIDONG LI^{3,25}, MATTHEW A. MALKAN²⁶, ILAN MANULIS¹, THOMAS MATHESON²⁷, NICHOLAS A. MOSKOVITZ²⁸, PHILIP S. MUIRHEAD⁸, PETER E. NUGENT^{3,17}, ERAN O. OFEK¹, ROBERT M. QUIMBY²⁹, JOSEPH W. RICHARDS^{3,30}, NATHANIEL R. ROSS²⁶, KINCHEN J. SEARCY³¹, JEFFREY M. SILVERMAN³, NATHAN SMITH³², ANDREW VANDERBURG³, AND EMMA S. WALKER¹³

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ABSTRACT

We present the discovery and extensive early-time observations of the Type Ic supernova (SN) PTF12gzk. Our finely sampled light curves show a rise of 0.8 mag within 2.5 hr. Power-law fits $[f(t) \propto (t - t_0)^n]$ to these data constrain the explosion date to within one day. We cannot rule out the expected quadratic fireball model, but higher values of n are possible as well for larger areas in the fit parameter space. Our bolometric light curve and a dense spectral sequence are used to estimate the physical parameters of the exploding star and of the explosion. We show that the photometric evolution of PTF12gzk is slower than that of most SNe Ic, and its high ejecta velocities ($\sim 30,000 \text{ km s}^{-1}$ four days after explosion) are closer to the observed velocities of broad-lined SNe Ic associated with gamma-ray bursts (GRBs) than to the observed velocities in normal Type Ic SNe. The high velocities are sustained through the SN early evolution, and are similar to those of GRB-SNe when the SN reach peak magnitude. By comparison with the spectroscopically similar SN 2004aw, we suggest that the observed properties of PTF12gzk indicate an initial progenitor mass of 25–35 M_{\odot} and a large ($5\text{--}10 \times 10^{51} \text{ erg}$) kinetic energy, close to the regime of GRB-SN properties. The host-galaxy characteristics are consistent with GRB-SN hosts, and not with normal SN Ic hosts as well, yet this SN does not show the broad lines over extended periods of time that are typical of broad-line Type Ic SNe.

¹ Department of Particle Physics and Astrophysics, The Weizmann Institute of Science, Rehovot 76100, Israel.

² email: sagi.ben-ami@weizmann.ac.il .

³ Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA.

⁴ INAF, Osservatorio Astronomico di Padova, Italy.

⁵ Max-Planck Institute for Astrophysics, Garching, Germany.

⁶ Kavli Institute for Theoretical Physics, Kohn Hall, University of California, Santa Barbara, CA 93106-4030, USA.

⁷ New York University, Center for Cosmology and Particle Physics, Department of Physics, 4 Washington Place, New York, NY 10003

⁸ Cahill Center for Astrophysics, California Institute of Technology, Pasadena, CA, 91125, USA.

⁹ Las Cumbres Observatory Global Telescope Network, 6740 Cortona Drive, Suite 102, Santa Barbara, CA 93117, USA.

¹⁰ Department of Physics, Broida Hall, University of California, Santa Barbara, CA 93106, USA.

¹¹ Department of Astronomy, San Diego State Univer-

sity, San Diego, CA 92182, USA.

¹² CEOU/Astronomy Program, Dept. of Physics & Astronomy, Seoul National University, Seoul, Korea.

¹³ Scuola Normale Superiore di Pisa, Piazza dei Cavalieri 7, 56126 Pisa, Ital

¹⁴ INAF, Astronomical Observatory of Trieste, Via G.B. Tiepolo 11, I-34143 Trieste, Italy.

¹⁵ Harvard Center for Astrophysics and Las Cumbres Observatory Global Telescope Network Fellow.

¹⁶ Department of Physics (Astrophysics), University of Oxford, DWB, Keble Road, Oxford, OX1 3RH, UK.

¹⁷ Astrophysics Research Institute, Liverpool John Moores University, UK.

¹⁸ Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.

¹⁹ George P. and Cynthia Woods Mitchell Institute for Fundamental Physics & Astronomy, Department of Physics and Astronomy, Texas A&M University, 4242 TAMU, College Station, TX 77843, USA.

²⁰ Department of Physics & Engineering, Palomar College, San Marcos, CA 92069, USA.

²¹ Astronomy & Astrophysics, 525 Davey Laboratory,

1. INTRODUCTION

A core-collapse supernova (CCSN) happens when a star having an initial mass $M \gtrsim 8 M_{\odot}$ ends its life in a catastrophic explosion. Observationally, CC-SNe are divided into three groups based on their observed spectra: SNe II show large amounts of hydrogen, SNe Ib exhibit helium but little or no hydrogen, and SNe Ic do not show significant amounts of hydrogen or helium (for a review, see Filippenko 1997).

SNe Ic are heterogeneous. Their luminosity, ejected mass, and kinetic energy span over an order of magnitude, from the subluminous SN 2004aw to the overluminous SN 1998bw (Drout et al. 2011; Mazzali et al. 2009). The light-curve shapes of different events are also quite diverse. A subclass of SNe Ic whose spectra are characterized by broad lines (Type Ic-BL; prototype SN 1998bw) is the only one for which clear evidence of an association with gamma-ray bursts (GRBs) exists (GRB-SNe; see Woosley & Bloom 2006 for a review). Superluminous SNe (SLSNe) of Type Ic are even more powerful (Gal-Yam 2012, and references therein), but these probably result from a different physical mechanism. While SNe Ic are common in the center of high-metallicity galaxies (Anderson et al. 2012), SLSNe-I and broad-lined GRB-SNe tend to be found in dwarf hosts (Modjaz et al. 2008; Arcavi et al. 2010; Neill et al. 2011), giving untar-geted sky surveys an advantage over targeted surveys in detecting these types of cosmic explosions.

The Palomar Transient Factory (PTF; Law et al. 2009; Rau et al. 2009) is a wide-field untar-geted sky survey which explores the transient optical sky. It uses the PTF CFH12k camera mounted on the Palomar 48-inch telescope (P48). PTF's short observing cadence and real-time capability (e.g., Gal-Yam et al. 2011) enables the discovery

and study of SNe at early stages of the explosion. In this Letter we report the discovery and study of PTF12gzk, a peculiar SN Ic in a dwarf star-forming galaxy located at redshift $z = 0.0137$ (distance 57.8 Mpc, distance modulus 33.8 mag, assuming $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

2. DISCOVERY

PTF12gzk was discovered on 2012 July 24.3 (UT dates are used herein) at $\alpha(\text{J2000}) = 22^{\text{h}}12^{\text{m}}41.53^{\text{s}}$ and $\delta(\text{J2000}) = +00^{\circ}30'43.1''$, in the dwarf galaxy SDSS J221241.53+003042.7 (within the SDSS/Stripe 82 footprint), as part of a coordinated PTF-JVLA³³ survey³⁴. The discovery magnitude was 20.66 in the r band³⁵, and it was not detected down to mag 21.6 (3σ) in previous PTF images obtained on July 19 (Ben-Ami et al. 2012).

Shortly after discovery, we initiated an extensive follow-up campaign in all wavebands, including our *Hubble Space Telescope* (HST) Target-of-Opportunity (ToO) program for STIS ultraviolet (UV) spectroscopy of a stripped-envelope SN (Cycle 19, GO-12530; PI Filippenko) and *Swift* X-ray and UV photometry (Cycle 8, PID 8110099; PI Kasliwal), the results of which are presented herein (see Figures 1 and 2 for photometry and spectroscopy, respectively). We also triggered radio and millimeter observations using the JVLA (program 12A-363; PI Horesh) and the Combined Array for Research in Millimeter-wave Astronomy (program 12A-c0945; PI Horesh); see Horesh et al. (in preparation).

3. HOST-GALAXY ANALYSIS

An image and a spectrum of the host galaxy obtained by the SDSS prior to explosion are shown in Figure 2. The SN exploded very close to the center of the host galaxy (offset $0.0''$ N and $0.4''$ E). We downloaded the host-galaxy spectrum from the SDSS 9th Data Release (DR9; Ahn et al. 2012). After correcting for the host-galaxy redshift, we measure integrated emission-line fluxes using standard procedures via *splot* in IRAF, and follow Perez-Montero & Diaz (2003) to compute statistical errors. Using the SDSS Petrosian magnitudes, correcting for Galactic and host-galaxy extinction (see below), and applying K -corrections via *kcorrect* (v4.2, Blanton & Roweis 2007) at the host-galaxy redshift, we derive an absolute magnitude

³³ The Jansky Very Large Array is operated by the National Radio Astronomy Observatory (NRAO), which is a facility of the National Science Foundation (NSF), operated under cooperative agreement by Associated Universities, Inc. (AUI).

³⁴ It was also independently discovered by the La-Silla Quest (LSQ) and Pan-Starrs1 (PS1) surveys, and designated LSQ 2012dwl and PS1-12baa, respectively.

³⁵ PTF magnitudes are given in the PTF natural-magnitude system (Ofek et al. 2012), with respect to the SDSS r -band magnitudes.

Penn State University, University Park, PA 16802, USA.

²² Department of Physics, University of California, San Diego, La Jolla, CA 92093, USA

²³ Galileo Galilei-INAF, TNG, Tenerife, Spain.

²⁴ Observatories of the Carnegie Institution for Science, 813 Santa Barbara St, Pasadena, CA 91101, USA.

²⁵ Deceased 2011 December 12.

²⁶ Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA.

²⁷ National Optical Astronomy Observatory, NOAO System Science Center, 950 North Cherry Avenue, Tucson, AZ 85719, USA.

²⁸ Carnegie Institution of Washington, Department of Terrestrial Magnetism, 5241 Broad Branch Road, Washington, DC 20008 USA.

²⁹ Kavli IPMU, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba, 277-8583, Japan.

³⁰ Department of Statistics, University of California, Berkeley, CA 94720-7450, USA.

³¹ San Diego Astronomy Association, P.O. Box 23215, San Diego, CA 92193-33125, USA.

³² Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA.

of $M_r = -14.8$. This is an extremely underluminous dwarf galaxy, well below the Large and Small Magellanic Clouds. It is one of the least luminous CCSN host galaxies discovered by PTF, and it is not a common host galaxy for a SN Ic that is not a SN Ic-BL — even those found via untar-geted surveys (Arcavi et al. 2010). In addition, the clear detections of numerous bright emission lines allow us to apply standard diagnostics of the star-formation rate (SFR), extinction, and metallicity to this galaxy.

3.1. Star-Formation Properties

Using the observed intensity ratio of $H\alpha/H\beta$, and assuming the Case B recombination value of 2.86 and the Cardelli et al. (1989) extinction law with $R_V = 3.1$, we estimate a reddening of $E(B - V) = 0.14 \pm 0.05$ mag. The values of the intensity ratios $[N\ II]/H\alpha$ and $[O\ III]/H\beta$ indicate that the prominent emission lines are due to recent vigorous star formation rather than to an active galactic nucleus (Baldwin et al. 1981). Furthermore, we do not detect any absorption features nor a Balmer break that may indicate the presence of an older stellar population.

Using the relations of Levesque et al. (2010), we derive a rest-frame equivalent width of $H\beta$, $EW_{H\beta} = 23.3 \pm 1\ \text{\AA}$, and an age of 6.4 ± 0.1 Myr for the young stellar population at the measured metallicity of the host ($Z = 0.004$; see below). From the measured integrated $H\alpha$ emission-line flux, corrected for extinction, we obtain $L(H\alpha) = (16 \pm 2) \times 10^{38}\ \text{erg s}^{-1}$, which translates to $SFR(H\alpha) = 0.02 \pm 0.002\ M_\odot\ \text{yr}^{-1}$ using the conversion from Kennicutt (1998). Since the SDSS spectrum was obtained through a $3''$ radius fiber encompassing an area of $2.2\ \text{kpc}^2$, and the Petrosian radius (from DR9) is twice the radius of the SDSS fiber, this derived SFR represents only a lower limit to the global SFR.

3.2. Oxygen Abundance

For computing the oxygen abundance (Modjaz et al. 2011), we correct the detected emission-line fluxes of $[O\ III]$, $[N\ II]$, $H\beta$, and $H\alpha$ for reddening, and employ the scales of Pettini & Pagel (2004, PP04-O3N2) and of Kewley & Dopita (2002, KD02) to obtain values of $12 + \log(O/H)_{PP04-O3N2} = 8.12^{+0.04}_{-0.02}$ and $12 + \log(O/H)_{KD02} = 8.13^{+0.05}_{-0.04}$, respectively. We conclude that the metallicity of the host galaxy is $0.2\text{--}0.3\ Z_\odot$, having used the solar oxygen abundance of $12 + \log(O/H) = 8.69$ (Asplund et al. 2009).

The oxygen abundance of the PTF12gzk host is well below that of the hosts of normal SNe Ic found via untar-geted surveys as presented by Modjaz et al. (2011; mean $12 + \log(O/H)_{PP04} = 8.7 \pm 0.1$) and Sanders et al. (2012, $12 + \log(O/H)_{PP04} = 8.61 \pm$

0.2). Indeed, it is much closer to that of the hosts of SNe Ic-BL and GRB-SNe (Modjaz et al. 2008; Sanders et al. 2012), and of SLSNe-I (Young et al. 2010; Stoll et al. 2011).

4. OBSERVATIONS

4.1. Photometry

Optical photometry of PTF12gzk was obtained using multiple telescopes (Table 1). All data were calibrated with respect to the SDSS catalog. Light curves of PTF12gzk are shown in Figure 1.

The optical data were reduced using standard IRAF procedures for aperture photometry (FTS data were reduced using PSF photometry via DoPHOT; Schechter et al. 1993). We subtract reference templates from the P48 and P60 data to remove contamination from the host. Pre-explosion templates were not used for other data, but the contribution from the underlying galaxy ($g, r, z = 19.05, 19.03, 18.75$ mag from SDSS) is negligible. The data were calibrated to SDSS stars in the field, using the transformation equations given by Jordi et al. (2006) to place the local standards on the Johnson-Cousins system.

Infrared (IR) photometry of PTF12gzk (Table 1) was obtained using the Wide Field Camera mounted on the United Kingdom Infrared Telescope (UKIRT-WFCAM) using SExtractor, and calibrated with respect to the 2MASS catalog (magnitude errors < 0.07 mag) using the relation of Hodgkin et al. (2009).

We adopt Galactic extinction corrections from NED. The absence of strong Na I D lines as well as the blue early-time spectrum (see below) suggest negligible extinction by the host galaxy.

During the first night of observation, PTF12gzk brightened by ~ 0.8 mag in less than 2.5 hr to 19.85 in the r band; we thus obtained remarkably early coverage of a SN Ic. By fitting fourth-degree polynomials to the full light curves, we find that the SN peaked at $r = 15.2$ mag on August 14, $g = 15.55$ on August 8, and $B = 16$ on August 4. On August 15, PTF12gzk peaked in the i band.

We have calculated a bolometric light curve by integrating the flux in the $BgVrRiIJHK$ filters. When lacking IR photometry, we assume a constant IR flux, found to be $\sim 18\%$ from synthetic photometry using TSPEC IR spectra, (see § 4.2). We estimate that the lack of IR (UV) coverage prior to August 7 introduces an uncertainty of $\sim 10\%$ from the small variation seen in the IR contribution ($< 5\%$ with respect to the overall flux) between August 4 (the first TSPEC IR spectrum) and August 12. Uncertainties introduced by the lack of UV photometry are $\sim 5\%$ from the even smaller variation in the UV contribution ($< 2\%$ relative to the overall flux). The bolometric light curve is given in Figure 1 and shows a rise time of 18 ± 1 day, similar to that

in the r band.

PTF12gzk was observed with the X-Ray Telescope (XRT) and the Ultraviolet/Optical Telescope (UVOT) onboard the *Swift* satellite. XRT measurements, beginning at 13:39 on July 31, detected no source at the location of PTF12gzk; we estimate a dead-time corrected limit on the XRT count rate of $< 2 \times 10^{-3}$ cps. Assuming a power-law spectrum with a photon index of 2, this corresponds to a limit on the X-ray flux of $< 7 \times 10^{-14}$ erg cm $^{-2}$ s $^{-1}$. UVOT observations, beginning at 11:30 on July 31, showed that PTF12gzk had a magnitude of 16.86 in UVW1 (260 nm). Later measurements taken on August 11 showed a decrease of ~ 0.7 magnitudes in UVW1, and magnitudes of 18.02 in UVM2 (220 nm) and 17.83 in UVW2 (190 nm).

4.2. Spectroscopy

Extensive spectroscopy of PTF12gzk was performed, and detailed analysis will be provided in a future paper. A selection of optical spectra is shown in Figure 2.³⁶

The first spectrum was obtained on July 27, revealing the object to be a peculiar SN I with a blue continuum, reminiscent of the blue continuum observed in the early-time spectra of SN 2006aj (Mazzali et al. 2006b). Initially it was difficult to classify the spectrum securely, but later optical spectra resemble those of SNe Ic, with an absence of prominent He I lines (Ben-Ami et al. 2012).

The August 1 spectrum was taken with the FLOYDS spectrograph mounted on the FTN, a low-dispersion spectrograph ($R \approx 400$) with a single, fixed grating and a cross-dispersing prism, placing the first- and second-order spectra onto the CCD with a single-exposure wavelength coverage of 320–1000 nm. While the identical twin FLOYDS spectrographs on FTN and FTS will ultimately be robotically operated, the present spectrum was taken during hardware commissioning under human control.

Classification with the help of SNID (Blondin & Tonry 2007) of the August 9 Lick 3-m/Kast spectrum suggests that the best fit is to the peculiar SN Ic SN 2004aw near peak brightness (Taubenberger et al. 2006). All spectra show prominent, broad absorption lines of Ca II, Si II, Fe II, and O I, with SYNOW fits yielding maximum velocities of $\sim 35,000$ km s $^{-1}$ for the July 27 spectrum, and $\sim 20,000$ km s $^{-1}$ for the August 9 spectrum. See Figure 3 and § 5 for further discussion.

The absence of the $2.1 \mu\text{m}$ He I feature in the IR TSPEC spectrum taken on August 7 (Figure 3,

bottom-right panel) suggests that He is not abundant in the envelope (Hachinger et al. 2012). While a strong absorption line is present at $1 \mu\text{m}$, which could be identified with He I $1.0830 \mu\text{m}$, there is possible contamination from other elements such as C, Mg, S, and Ca (Sauer et al. 2006; Hachinger et al. 2012; Dessart et al. 2012).

The first *HST* UV spectrum, obtained by the Space Telescope Imaging Spectrometer with the near-UV Multi-Anode Microchannel Array (STIS/NUV-MAMA), was taken between 20:06 August 6 and 03:35 August 7, with a total exposure time of 11,278 s. We also obtained optical spectra with the STIS/CCD, using grisms centered at 430 nm and 750 nm. A mosaic of all three *HST* spectra is given in Figure 3, with a focus on the UV spectrum in the bottom-left panel. The flux deficit with respect to blackbody spectra seen in the STIS/MAMA UV spectrum is characteristic of all SNe I (Panagia 2007) and indicates strong line blanketing, evidence for a highly mixed outer envelope devoid of hydrogen. Full analysis of the *HST* UV spectra will be presented by Ben-Ami et al. (in prep.).

5. DISCUSSION

PTF12gzk is a luminous SN Ic, near the high end of SN Ic luminosity distribution (Drout et al. 2011). Photometrically, it exhibits a slow rise to peak R -band magnitude of 18 days, with the B -band magnitude peaking ~ 10 days earlier. This is a large gap relative to other SN I, though similar to SN 2004aw (Taubenberger et al. 2006); it is caused by metal-line absorption from heavy elements in the outer layers of the ejecta, as is evident from spectra taken after August 1.

A least-squares fit to a $f(t) \propto (t - t_0)^n$ behavior of our well-sampled early photometry places the explosion date between 10 and 40 hr prior to our discovery at the 95% confidence level. We cannot rule out the expected quadratic fireball model, but higher values of n are possible as well for larger areas in the fit parameter space. (see Figure 1, bottom panel).

Spectroscopically, PTF12gzk exhibits high expansion velocities, $\sim 30,000$ km s $^{-1}$ (absorption velocity of Si II), faster than the expansion velocities seen in SN 2004aw at similar epochs. Other SNe Ic with similar velocities are broad-lined SNe Ic (Figure 3, top-right panel), some of which are associated with GRBs (Woosley & Bloom 2006, and references within), while no such association was determined for PTF12gzk (see also SN 2009bb; Soderberg et al. 2009). Most similar is SN 2003lw, a SN associated with a GRB (Mazzali et al. 2006a).

A possible explanation is a burst misaligned with our line of sight, or a failed GRB. Such a scenario is further supported by the host-galaxy characteristics, resembling those of a broad-lined SN Ic host

³⁶ All ground-based spectra presented in this paper are released on WISEREP, <http://www.weizmann.ac.il/astrophysics/wiserep/>; Yaron & Gal-Yam 2012.

galaxy. We know of no typical SN Ic exploding in a host with similar luminosity and oxygen abundance. The observed relatively narrow lines give a dispersion of $\Delta v/v \approx 0.25$, compared to ~ 1 in the case of broad-lined SNe Ic, and may suggest a non-spherical explosion geometry (Leonard et al. 2006), or that the ejecta mass is high or has a very steep density gradient. Late-time, nebular spectra will probe the geometry of the explosion in more detail.

From the Si II line velocity at peak brightness for PTF12gzk ($15,300 \text{ km s}^{-1}$ from the August 12 spectrum) and SN 2004aw ($12,400 \text{ km s}^{-1}$; Deng et al., in prep.), and the rise time of these two SNe, we use the following scaling relations (Arnett 1982, Mazzali et al. 2009; see also Mazzali et al., in prep.) to estimate the physical properties of PTF12gzk: $\tau \approx \kappa^{1/2} M^{3/4} E^{-1/4}$ and $v = (2E/M)^{1/2}$, where τ is the light-curve rise time, E is the kinetic energy, and κ is the opacity. The derived ejecta mass is $7.5 M_{\odot}$ ($6\text{--}12 M_{\odot}$), pointing to a large initial progenitor mass of $25\text{--}35 M_{\odot}$, though the latter values are highly uncertain (Mazzali et al. 2000; Langer 2012). We derive a kinetic energy of $7.5 \times 10^{51} \text{ erg}$ ($5\text{--}10 \times 10^{51} \text{ erg}$), and a high ^{56}Ni mass of $0.37 M_{\odot}$. Using the V -band peak magnitude vs. nickel mass relation presented by (Perets et al. 2010), we get a ^{56}Ni mass of $0.35 M_{\odot}$, in agreement with the results derived from the scaling relations. These physical properties, as well as the high expansion velocities and the host-galaxy properties, are unlike those of normal SNe Ic, which typically occur in large hosts and have low ejecta masses, kinetic energies, and nickel masses ($2 M_{\odot}$, 10^{51} erg , and $0.2 M_{\odot}$, respectively; see Drout et al. 2011). Instead, they are reminiscent of GRB-SNe (Mazzali et al. 2009).

PTF12gzk is an outstanding example of a SN Ic in terms of expansion velocities, evolution timescale, the ejected mass, and the kinetic energy released in the explosion. We conclude that these properties point to the explosion of a massive star deficient in H and He, at the higher-mass end of SN Ic progenitors. This further illustrates the peculiar population of SNe Ic exploding in dwarf hosts (Arcavi et al. 2010), as seen also in the case of GRB-SNe and most SLSNe-I.

PTF12gzk demonstrates the advantages of using an untargeted sky survey such as PTF with an extensive network of instruments and telescopes in various wavebands to detect and rapidly characterize unusual cases of cosmic explosions.

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Date (MJD)	Instrument	Filter	Apparent Magnitude	1 σ Uncertainty
2456132.763	P48+CFH12k	<i>R</i>	20.66	0.12
2456132.779	P48+CFH12k	<i>R</i>	20.24	0.15
2456132.808	P48+CFH12k	<i>R</i>	20.13	0.08
52456132.809	P48+CFH12k	<i>R</i>	20.11	0.12
2456132.848	P48+CFH12k	<i>R</i>	20.02	0.07

TABLE 1

PTF12GZK PHOTOMETRY. DATA WERE OBTAINED USING THE P48+PTF CAMERA, THE PALOMAR 60-INCH TELESCOPE + GRB CAMERA, THE FAIRCHILD CAMERA ON THE 40-INCH TELESCOPE AT MT. LAGUNA OBSERVATORY (MLO), FS01 ON THE 2-M FAULKES TELESCOPE SOUTH (FTS), THE IO:O CAMERA ON THE LIVERPOOL TELESCOPE (LT), THE PI CAMERA ON THE WISE 1-M TELESCOPE, THE WEIZMANN INSTITUTE KRAAR 16-INCH TELESCOPE, AND THE 0.76-M KATZMAN AUTOMATIC IMAGING TELESCOPE (KAIT; FILIPPENKO ET AL. 2001). THE FULL SET OF PHOTOMETRIC DATA IS AVAILABLE IN THE ELECTRONIC VERSION OF THIS PAPER.

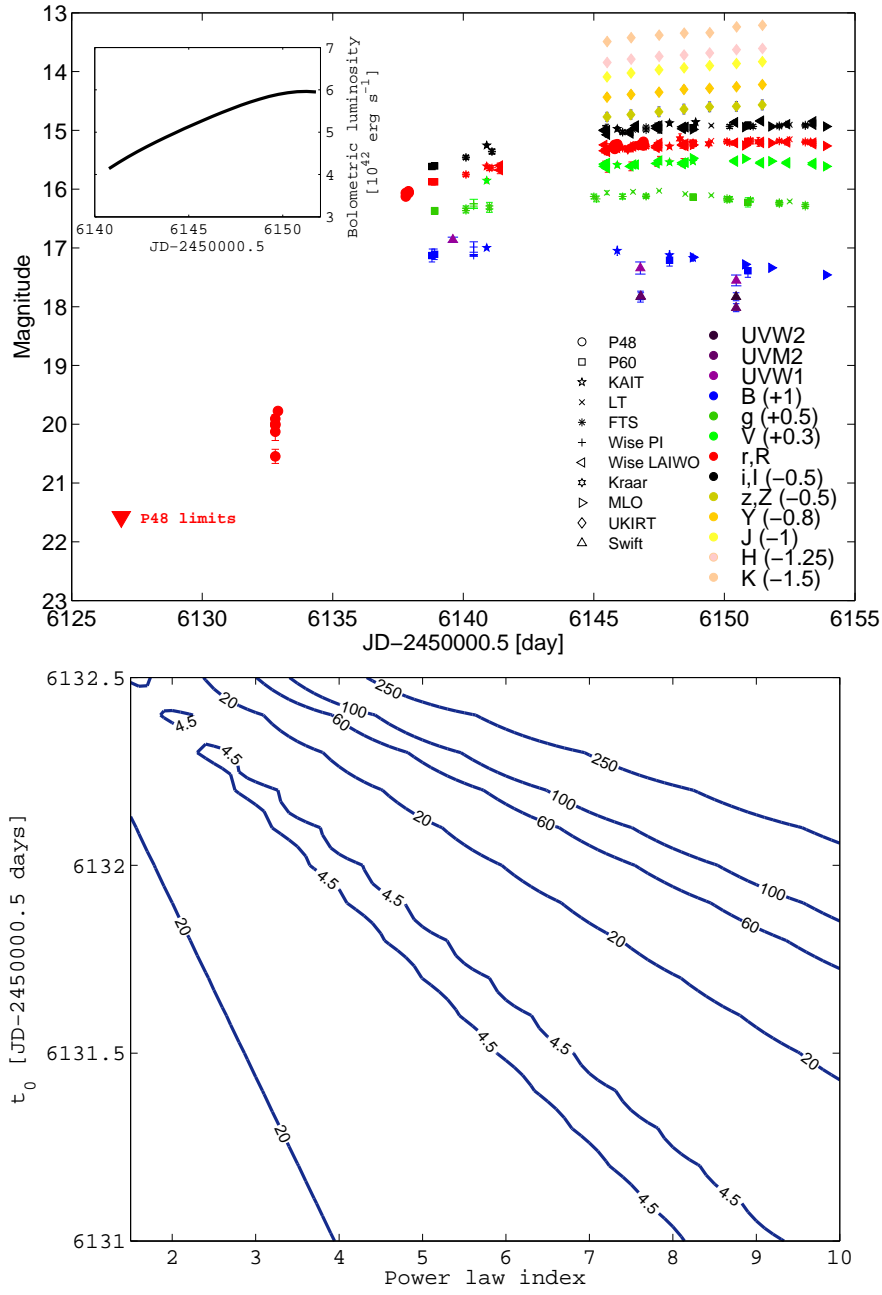


FIG. 1.— PTF12gzk photometry. **Top:** The long rise time and the large delay in peak magnitudes between bluer and redder filters is clear. **Inset:** A bolometric light curve derived from our UV-optical-IR data. **Bottom:** A χ^2 contour plot comparing power-law models with the first 2.5 hr of observations (see text). The value of the index n is not well constrained.

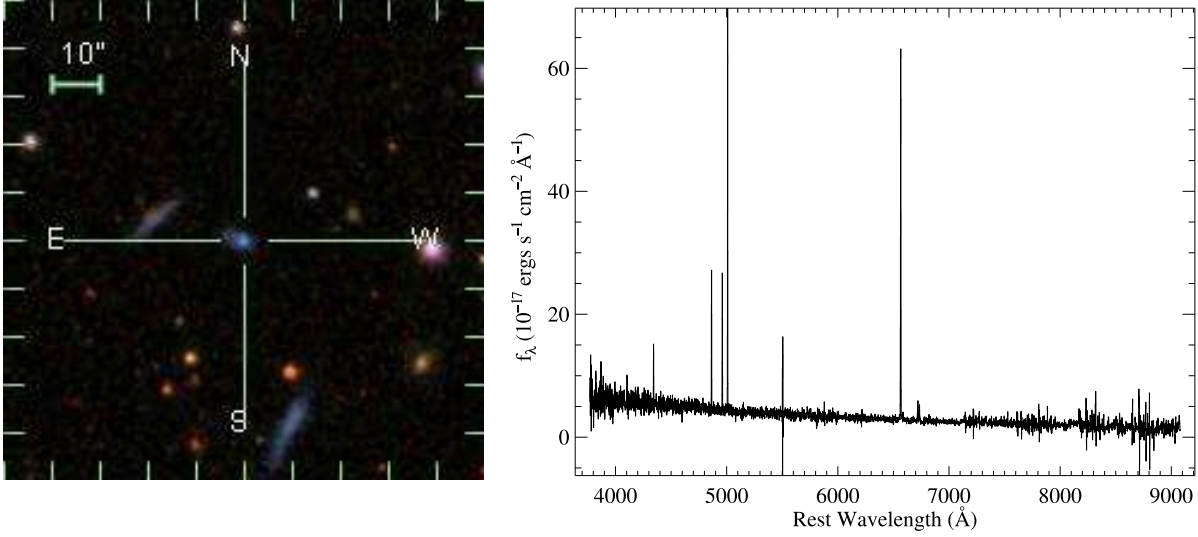
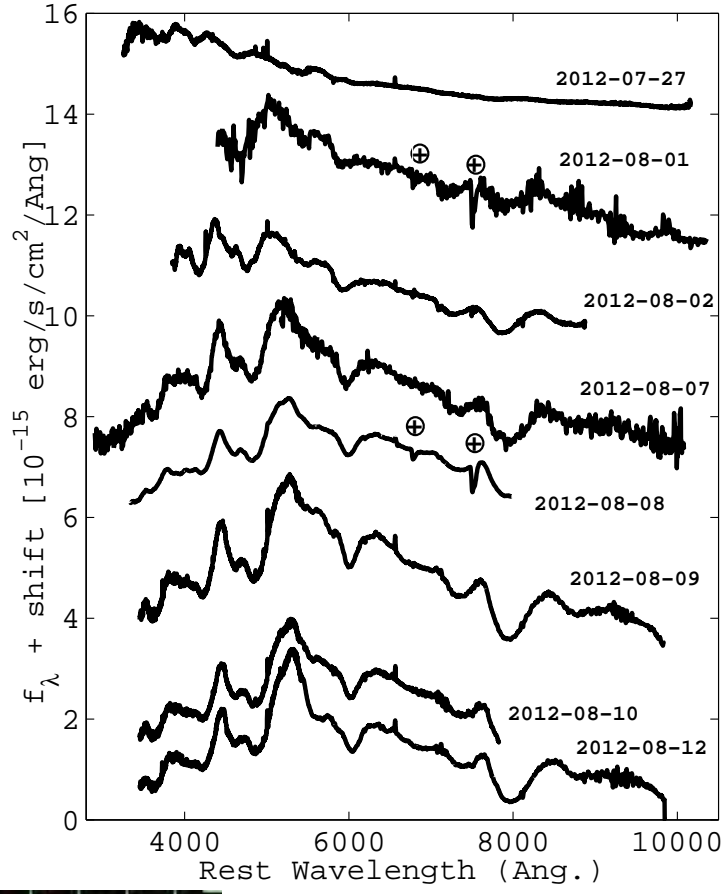


FIG. 2.— **Top:** PTF12gzk optical spectra; telluric features are marked. **Bottom:** The host galaxy of PTF12gzk. Left: SDSS image; note the blue color and small spatial size ($1'' = 280 \text{ pc}$). Right: SDSS spectrum; note the strong emission lines and blue continuum.

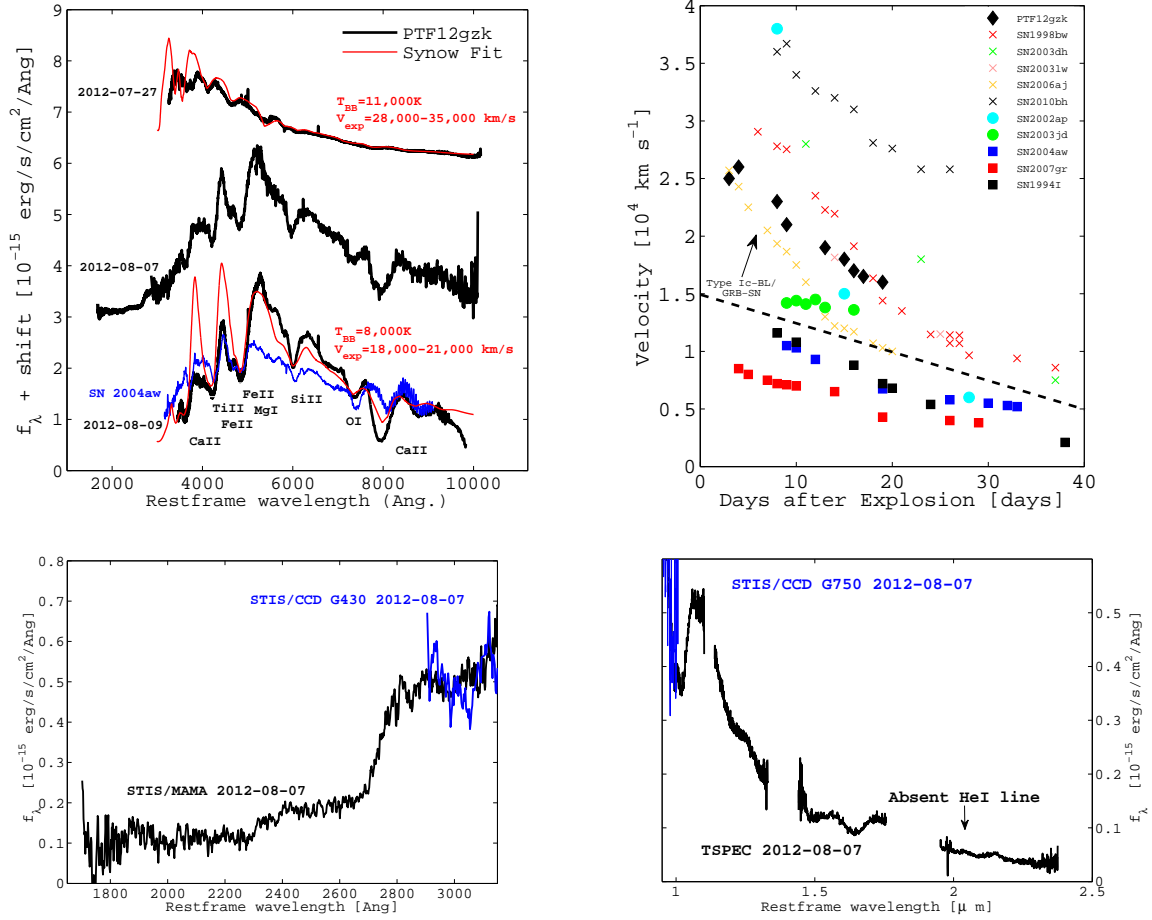


FIG. 3.— **Top left:** Spectroscopic analysis; top to bottom. The DBSP spectrum taken on July 27. An *HST* STIS/MAMA and STIS/CCD (G430 and G750) spectrum taken on August 7. A Lick/KAST spectrum taken on August 9. The continuum is consistent with blackbody temperatures of 11,000 K and 8000 K in the July 27 and August 9 spectra, respectively. A SYNOW fit shows that the spectrum is dominated by Ca II, Ti II, and Fe II lines at velocities of $35,000 \text{ km s}^{-1}$, and O I, Mg II, and Si II at $28,000 \text{ km s}^{-1}$ ($21,000 \text{ km s}^{-1}$ and $18,000 \text{ km s}^{-1}$, respectively, in the August 7 spectrum). The best match suggested by SNID (Blondin & Tonry 2007) is to a spectrum of SN 2004aw near peak brightness (blue curve). **Top right:** PTF12gzk has characteristic velocities of a broad-lined SN Ic. All SNe above the dashed line, besides PTF12gzk, are GRB-SNe (diamonds) or Type Ic-BL with no GRB association (circles), while those below it are normal SNe Ic (squares). Velocities are obtained through modeling of the spectrum or through direct measurements of Si II 6355 Å line (SNe 2010bh, 2002ap, 2003jd, 2004aw, and 2007gr). **Bottom left:** The *HST* STIS/MAMA UV spectrum taken on August 7. The flux deficit with respect to a blackbody spectrum indicates strong line blanketing, evidence for a highly mixed outer envelope. **Bottom right:** The Palomar 5-m TSPEC IR spectrum obtained on August 7, together with the long-wavelength end of the *HST* STIS/CCD spectrum.